GENERAL MILLS ELECTRONICS DIVISION
Aerospace Research
2003 East Hennepin Avenue
Minneapolis, Minnesota 55413

INVESTIGATION OF SPUTTERING EFFECTS ON
THE MOON'S SURFACE

Fourth Quarterly Status Report on
Contract NASw-751

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Prepared by:

    G. K. Wehner
    D. L. Rosenberg
    C. E. KenKnight

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Submitted by: *G. K. Wehner*

    G. K. Wehner, Director
    Surface Physics Laboratory

Approved by: *Sam P. Jones*

    Sam P. Jones
    Technical Director

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ABSTRACT

Additional hydrogen sputtering yields on metals and metal oxides have been obtained, confirming earlier values for Al, Ti, and Fe and revealing that chemical effects double the sputtering rate on SiO_2 relative to Si, for which yields of $0.018/H_2^+$ and $0.046/H_3^+$ at 7.5 keV were obtained. Helium yields have been determined using the same mass-analyzed ion beam hole-drilling technique as with hydrogen. Typical values at 7 keV/He^+ ion are 0.174 Al atoms, 0.091 Ti atoms, 0.143 Fe atoms, 0.175 Ni atoms, and 0.058 $AlO_{3/2}$ molecules, 0.027 TiO_2 molecules, 0.075 $FeO_{3/2}$ molecules. The ratio of a metal oxide yield to the metal yield expresses the degree to which oxygen modifies the sputtering of that metal. These ratios for Al (0.35) and Fe (0.6) are nearly independent of the choice of ion, H^+ or He^+, indicating absence of chemical effects. For Ti, the ratios of 0.3 for He^+ and 0.7-0.8 for H^+ possibly indicate the effects of solubility of hydrogen in Ti rather than chemical effects.

Bombardment of powdered basalt by ions from He and He-H_2 mixture plasmas does not result in accelerated surface darkening or alteration as one would expect from the higher yields associated with the heavier ion. This illustrates the importance of the chemical action of hydrogen. Surface darkening by hydrogen bombardment of a segment of the Holbrook meteorite has been observed and measured. The normal albedo was reduced from

0.30 to 0.12 by the equivalent of 10^4 years of solar-wind bombardment. Reflection curves and normal albedos are given for various oxides and minerals before and after exposure to simulated solar-wind bombardment equivalent to periods of up to 2×10^5 years.

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Author

I. INTRODUCTION

During this quarter, the following relevant literature concerning the nature of the lunar surface has come to our attention. Hapke[1] has described measurements of packing properties of fine dust which show that a rock powder of considerable depth could be maintained in a low-density state on the moon. He ground dunite to an average particle size of less than 10μ, baked it in an argon atmosphere, and sifted it through a 400-mesh screen again in an argon atmosphere. Other samples were not baked or kept under argon before testing but gave similar results. Bernett, et al[2] have measured the bearing capacity of basalt powder of various particle sizes in vacuums to 10^{-6} Torr. Salisbury,[3] et al have studied the adhesive behavior of silicate powders in ultrahigh vacuum. These data indicate that lunar surface materials will exhibit an appreciable shear strength. Murray and Wildey[4] have measured the $8-14\mu$ brightness temperature of the shaded lunar surface. Their results show a characteristic pattern of cooling inconsistent with the occurrence of a thick homogeneous dust layer. It appears that more highly heat conducting material either is exposed commonly on the surface or is covered by no more than a centimeter or so of strongly insulating dust. No difference in temperature distribution was observed between maria and uplands. This work ties in nicely with our own. Fung,[5] Fung and Moore,[6] and Hayre[7] have recently published papers concerning the determination of lunar surface structure and roughness by radar observation. According to Fung and Moore, there appears to be a wide distribution of structure size. Luminescence of the lunar surface has been studied by Kopal and Rackham.[8] Brightening of a large lunar area after a small solar flare has been recorded. The size of the area and duration of brightening rules out gas emission as a

cause. It would be of interest to determine the effect of our simulated solar-wind bombardment on known luminescent powders.

Additional sputtering yields have been obtained in the fourth quarter of this contract. The hole-drilling technique used with hydrogen has been extended to helium. Basalt powder surfaces have been bombarded in helium-hydrogen plasmas and helium plasmas in an attempt to determine the importance of the chemical reduction by hydrogen in darkening bombarded surfaces. A segment of the Holbrook meteorite has been darkened by simulated solar-wind bombardment. Reflection curves and normal albedos of most of the materials which we have studied under this contract are included in this report.

A Letter to the Editor of the Journal of Geophysical Research has been submitted entitled "Darkening of Powdered Basalt by Simulated Solar-Wind Bombardment". Results have been presented at the "24th Annual Conference of Physical Electronics", 25-27 March 1964 at MIT, Cambridge, Massachusetts, and at the "Symposium on Thermal Radiation of Solids", 4-6 March 1964 at San Francisco, California. A preprint of the paper given at the Thermal Radiation Symposium, as it will appear in the Proceedings, is enclosed.

II. SPUTTERING YIELDS UNDER HYDROGEN AND HELIUM ION BEAM BOMBARDMENT

The question of the role of chemical effects of hydrogen upon apparent sputtering rates under solar-wind bombardment has been repeatedly posed. An indirect attack upon this problem is the comparison of hydrogen and helium sputtering yields for various metals and their oxides, expressing the yields in each case in terms of metal atoms removed per incident ion. These yields are so low for protons (10^{-3} to 10^{-1} atoms/proton), even though the kilovolt energies of the solar-wind protons coincide with the region of maximum proton sputtering yield on most materials, that one to three orders of magnitude more hydrogen atoms must leave the bombarded surface per unit time than sputtered atoms. In view of this excess of hydrogen atoms, in view of the damage to the solid induced by the incident ions, and in view of the possibility of a stable end-product being rapidly removed from the reaction zone, it might be supposed that a finite depth of a metal oxide bombarded by hydrogen ions will be effectively reduced to the parent metal with the formation of water vapor. In that case, the sputtering yield of a metal oxide would be only slightly decreased below that of the parent metal and then only because of damage effects or the shortening of focused collision chains. On the other hand, helium sputtering should be hindered by the strong oxide bonds.

The results presented here indicate, to the contrary, that the addition of 3/2 to 2 oxygen atoms per metal atom to a target reduces the sputtering yield under either hydrogen or helium bombardment by essentially the same factor. That factor ranges from 0.3 to 0.8 for the metals surveyed.

The technique employed was the drilling of holes in thin foils with mass-analyzed hydrogen and helium-ion beams.[9] The current to the foil and the current passing through the foil were monitored in order to calculate the number of ions required to drill the hole. The oxide foils were prepared either by baking the metal foil in air or by compressing finely-divided powders of the pure oxide.[10] A thin layer of Ni or Ag, or both, was deposited on the resultant oxide foil to carry away the current and the heat of the beam. Sputtering was in a target region of background pressure known to be less than 10^{-6} Torr with current densities of 30 to 80 mA/cm^2 at the target. With these parameters it can be shown that the flux of a gas such as oxygen is much greater away from the target into the ambient than vice versa.

The sputtering yields for He$^+$ ions on Al, Ti, and Fe and their oxides are presented in Table I. The yields for Ni and Ag were also required in order to correct for the amount of charge required to sputter away the thin (9 and 4 microns, respectively) layers of Ni or Ag, or both, on the oxide foils and are also given. It was found possible to obtain 3 or 4 holes in each foil at differing He$^+$ energies, e.g., 9, 6.5, 5, and 3.5 keV, in that order. Because of charge exchange with He in the target region escaping from the ion source, a few fast neutrals are not bent by the magnetic field, but fall on the target where higher energy He$^+$ ions would strike. They cannot deform the shape of a previously drilled hole at higher energy, but could conceivably remove enough material to cause a discrepancy if the opposite sequence were followed. Besides, at the high current densities of the higher voltages, a greater background pressure can be tolerated so that one can take advantage of gradual clean-up before performing the low-energy sputtering.

Table I

(a) He$^+$ Yields on Metal Foils

Metal	kV	Y	$\Delta Y/Y$ (%)	Comments
Al	4.5	0.192	5	
	5.0	0.208	5	Large but steady drop in total ion current.
	6.5	0.172	3-5	Possible small beam shift, noisy arc current.
	7.0	0.178	3	
	7.0	0.170	3	
	9.0	0.164	3	
	9.0	0.123	---	Probable beam shift.
Ti	5.0	0.085	3	
	7.1	0.091	3	
	9.0	0.105	3	
Fe	5.0	0.099	3	30 mA/cm^2
	7.0	0.143	3	44 mA/cm^2
	9.0	0.136	3	56 mA/cm^2
Ni	5.0	0.161	3	
	6.5	0.174	3	
	9.0	0.178	3	
Ag	3.5	0.316	20	Ragged hole, low current density (3.7 mA/cm^2)
	5.0	0.440	5	Possibly Y is a few % high due to 3.5 kV sputtering.
	6.5	0.310	---	Probable beam shift: very large shift in preceding 2 hours at 9.0 kV.

(b) He$^+$ Yields on Metal Oxide Foils

Oxide	kV	Y	$\Delta Y/Y$ (%)	Comments
$AlO_{3/2}$	5.0	0.063	3-5	Powder foil.
	7.0	0.058	3-5	
TiO_x	6.0	0.027	3-5	Baked to x = 1.86.
FeO_x	4.5	0.098	3	Baked to x = 1.5, foil non-magnetic.
	6.0	0.072	3	The foil appears blistered so uniformity is open to question.
	9.0	0.080	3	

The form of the He^+ sputtering yield curve for Al is a gradual decline with He^+ energy increase in the 4.5 to 9.0 keV range studied. The effect of a shift in beam position during bombardment is an anomalously low yield; one of the 9.0 keV results should thus be ignored. Data are scant for Fe and Ti, but the ratios of the yields on a single foil are particularly reliable, so it is probably the case that the maximum He^+ yield on Fe occurs near 7 keV, while it has not yet occurred at 8 keV for Ti. Notice that the yields decrease in order Al, Fe, Ti while the energy of the maximum yield for a target increases in that same order. Such a feature has been noted before for the H^+ ion.[11] The situation for Ni appears to be comparable to that for Fe. The results for Ag are not very reliable because of various experimental difficulties so that additional data are needed. However, one has data for He^+ on Ag by Grønlund and Moore[12] who employed a radioactive tracer technique. They found a maximum sputtering yield of 0.43 atoms/ ion near 4 keV and a decline to 0.40 atoms/ion by 10 keV. Agreement of our 5.0 keV sputtering yield of 0.44 atoms/ion is therefore good, perhaps fortuitously.

The sputtering yields of aluminum oxide, expressed as $AlO_{3/2}$ molecules/He^+ so as to be equivalent to stating the number of sputtered Al atoms/He^+, are lower than Al by a factor of 0.33. The similarly electropositive titanium has its "dioxide" yield reduced by 0.31. The composition of the TiO_x was obtained from the mass increase upon baking in air for several hours at 1000°C as $x = 1.86$. Unfortunately, the comparably baked Fe foils tended to be blistered so that the uniformity of

these foils is open to question. In particular, the 4.5 keV He^+ yield is hardly reduced below the yield on the pure metal as though a thin spot on the oxide foil were encountered. Two other yields on the same oxide foil were smaller than yields on metallic Fe by factors of 0.52 and 0.59.

The sputtering yields for H_2^+ and H_3^+ ions on Al, Ti, Fe, and Si and their oxides are presented in Table II. Although most of these data have been discussed before,[10] we present them here for comparison. The result for Si was obtained by preparing a powder foil by the same technique employed with certain oxides. The use of the powder foil technique may introduce a further reduction in sputtering yields due to the extreme roughness of the target on a microscopic scale. Such an effect is indicated by the results for $FeO_{3/2}$ where the powder foil has a sputtering yield of about 0.7 of that of the baked foil. It is obviously of interest: (1) to extend this comparison to other elements in order to determine if the factor of 0.7 generally obtains, or (2) to obviate this effect by preparation of metal and oxide powder foils. The powder foil of TiO_2 can surely be prepared and will serve as a further check on the powder foil technique. The latter alternative was attempted for Si. The surprising result was found that the apparent sputtering yield for SiO_2 is at least a factor of 2 larger than that for Si. A special effort was made to make the runs similar in every way. Powder grain size was determined by a common sieving procedure (Al_2O_3 powder foils are of the same grain size). The Ni films were deposited simultaneously. Background pressures and ion current densities were nearly identical. The Si yields are of the expected magnitude relative to Be, Al, and Ti.

Table II

(a) $H_{2,3}^+$ Yields on Metal Foils

Metal	kV	$10^3 Y_2$	$10^3 Y_3$	$\Delta Y/Y$ (%)	Comments
Al	7.0	29	42	3	Single run.
Ti	7.0	11	16	4	Two runs.
Fe	6.5	24	33	4	Derived from yield curves.
Si	7.5	18	46	10	Powder foil.

(b) $H_{2,3}^+$ Yields on Metal Oxide Foils

Oxide	kV	$10^3 Y_2$	$10^3 Y_3$	$\Delta Y/Y$ (%)	Comments
$AlO_{3/2}$	7.0	10.5	15.0	10	
	7.0	11.8	17.1	5	
TiO_x	6.0	7.5	12.9	5	Baked to x = 1.86.
	6.5	7.5	10.6	10	Possible beam shift.
FeO_x	6.5	12.7	20.4	5	Baked to x = 1.5. Questionable uniformity.
$FeO_{3/2}$	7.0	9.4	12.8	5	Powder foil.
SiO_2	7.5	83.0	92.0	10	Powder foil.

The ratio $Y_3/Y_2 = 2.5$ for Si is unusually large but the hole-drilling technique is rarely subject to undetectable systematic errors as large as 10% except those due to variations in foil thickness. It is quite possible additional data will revise the Si sputtering yields, but it is most implausible that SiO_2 yields will turn out to be less than the Si yields (it would involve two or more systematic errors involving factors of 2 to 5 in the present data). It must be concluded that chemical effects have been demonstrated in the Si-O-H system.

The factors by which the oxides of metals decrease hydrogen yields relative to the metals are about 0.38 for Al, 0.7-0.8 for Ti, 0.4 (powder) or 0.6 (baked) for Fe.

In conclusion, for Al or Fe, oxygen hinders sputtering by a factor that is quite independent of whether hydrogen or helium ions are used. The effect of oxygen is to reduce He^+ sputtering of Ti more than H^+ sputtering. Since Ti and Al are expected to be similar chemically with respect to hydrogen, and since the decrease in yield for He^+ is about 0.3 for both Ti and Al, the dissimilar decreases for H^+ ions should probably be laid to a peculiarity of the Ti-H solid system (H is very soluble in Ti and makes it brittle). Although it is not possible to say in these cases whether the oxygen leaves the lattice predominantly as atomic oxygen or in some molecular form, the net effect of the oxygen appears to be simply the addition of atoms which must be knocked loose by dynamics very similar to those in the parent lattice. The lighter oxygen mass results in better coupling to the light, fast-moving ions than is the case for the

massive metal atoms. As a result, the outer surface becomes enriched in metal atoms at equilibrium because oxygen atoms can be knocked loose from deeper in the lattice. Such a surface is darkened through "metallic" absorption as the experiments show.

IV. BOMBARDMENT OF BASALT IN HELIUM
AND HELIUM-HYDROGEN PLASMAS

An experiment was performed in an attempt to determine whether simultaneous hydrogen-ion and helium-ion bombardment as present in the solar wind may lead to sputtering yields or surface alterations which are increased out of proportion due to the combination of chemical and physical processes. The apparatus used in hydrogen bombardment was modified by the addition of a helium source controlled by a needle valve. The H_2 was admitted through a palladium leak.

During helium-hydrogen ion bombardment, the plasma appeared essentially as a helium plasma and the spectrum was that of helium with only the strongest H(I) lines appearing. These conditions were selected to maximize the effect of simultaneous bombardment. The total ion current density and sheath thickness were about the same as with hydrogen alone, i.e., the ion current density ranged from 1 to 2 mA/cm^2 and the average ion energy was $\sim$500 eV. In the experiment with the He-H_2 mixture, we cannot establish what the helium ion/hydrogen ion ratio is which bombards the surface. Neither the partial pressures nor the relative intensities of the spectral lines will give this information.

Basalt powders were bombarded in the He-H_2 plasma, in a helium plasma, and in a hydrogen plasma for $5\frac{1}{2}$ hours. The amount of darkening is quite similar in all three cases. The shapes of the reflection curves as shown in Figure 1 are similar and the normal albedos changed from an original value of 0.27 to 0.055 for helium-hydrogen, 0.065 for helium, and 0.050 for hydrogen. Control runs were made with just exposing the targets for
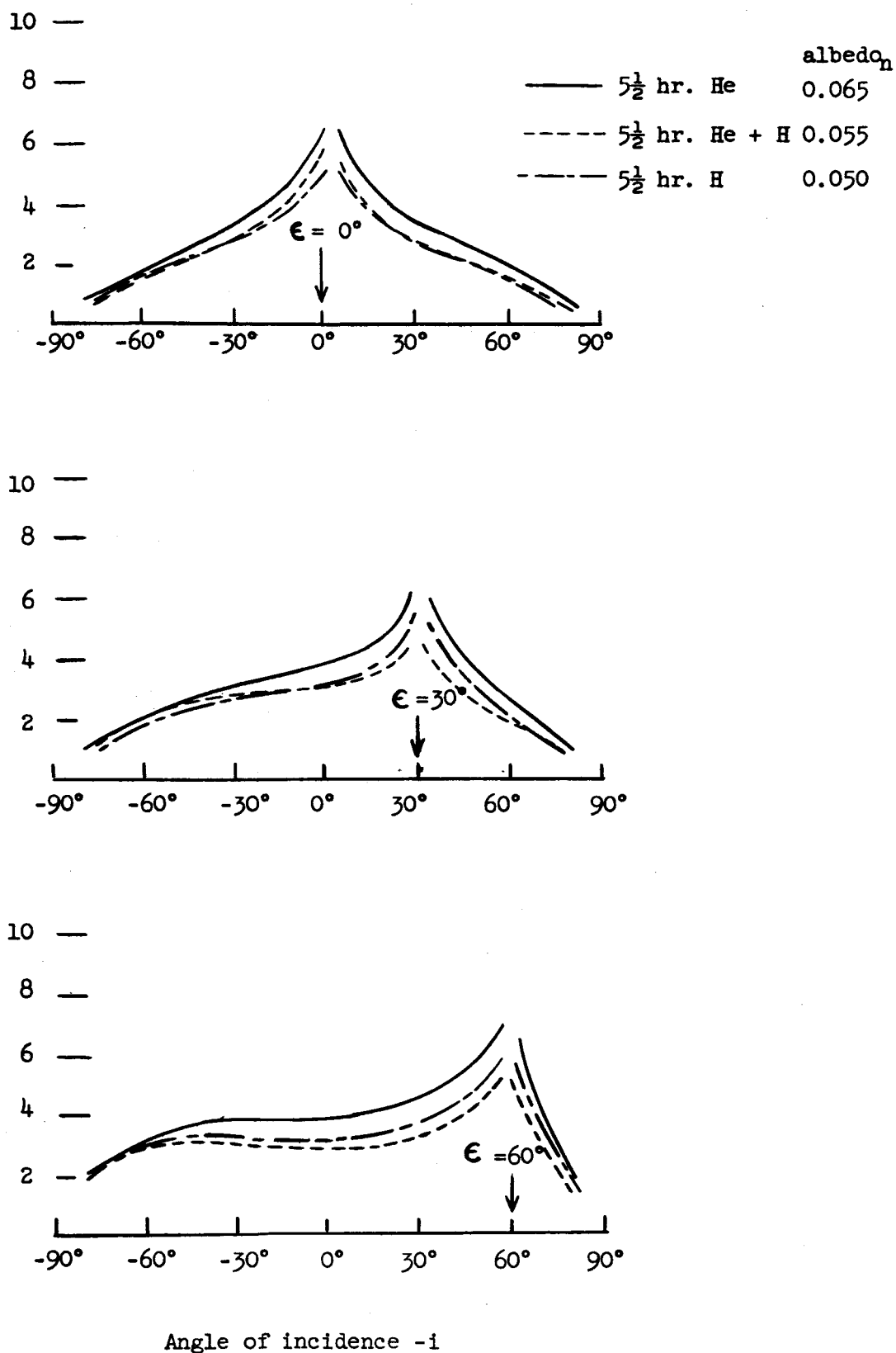
Figure 1 Reflection curves for basalt powder after helium,
helium-hydrogen, and hydrogen-ion bombardment.

$5\frac{1}{2}$ hours to the plasma and no rf potential applied to the target. In this case the target is only exposed to the UV from the discharge and a very low energy ion bombardment which arises from the slight negative charge on a floating electrode. The normal albedo changed in the hydrogen plasma to 0.12, in the helium-hydrogen plasma to 0.24, and in the helium plasma to 0.25. The reflection curves for plasma-exposed surfaces are shown in Figure 2. The result again indicates the importance of chemical effects in the case of hydrogen exposure. Even at very low hydrogen-ion energies the samples show considerable darkening, which is nearly absent in the case of low-energy, helium-ion bombardment. Simultaneous hydrogen- and helium-ion bombardment does not seem to accelerate surface alterations.
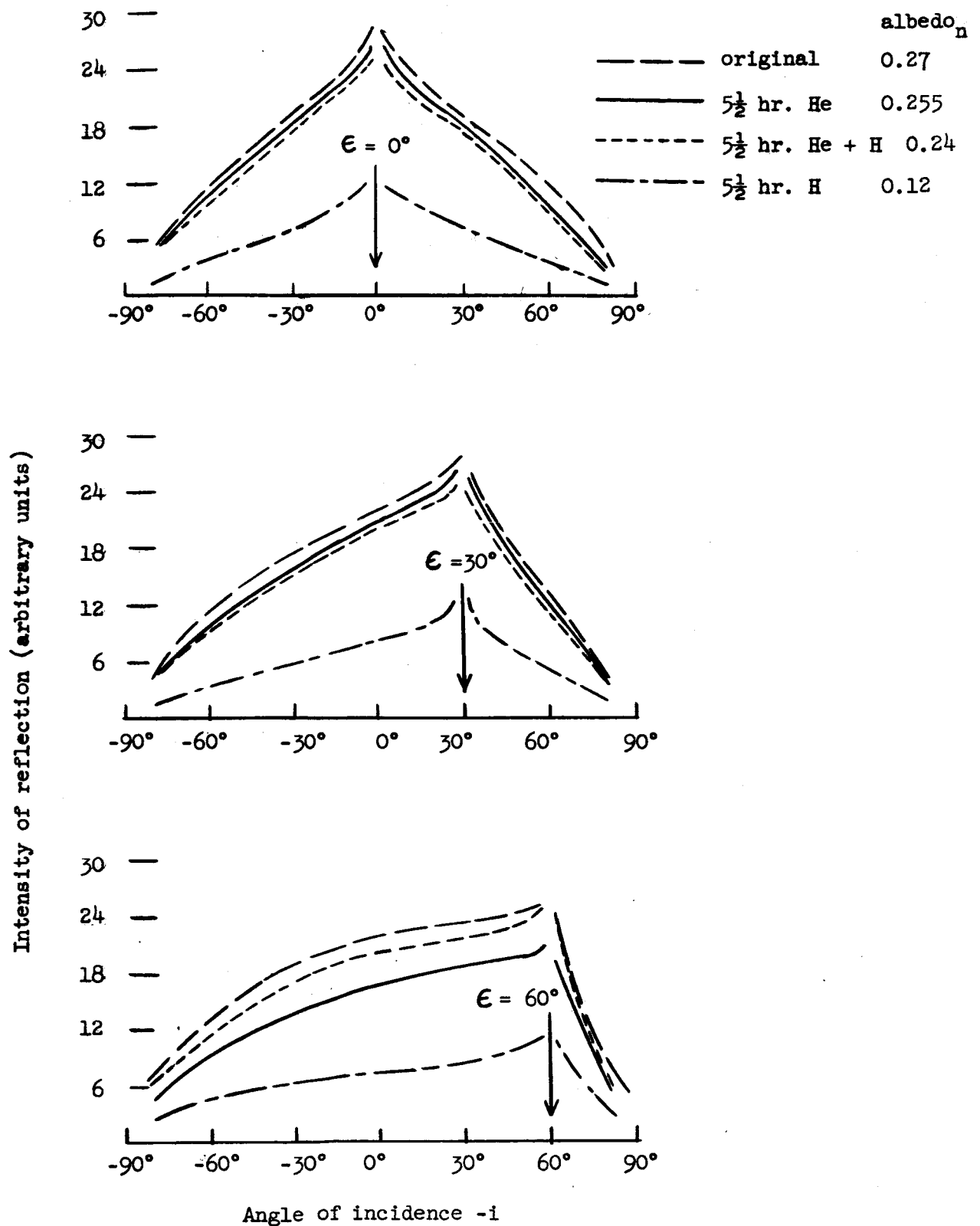
Figure 2   Reflection curves for basalt powder before and after
            exposure to helium, helium-hydrogen, and hydrogen plasmas.

V. HYDROGEN BOMBARDMENT OF A STONY METEORITE SURFACE

Several segments of the Holbrook and the Bruderheim meteorites were obtained from Dr. P. Gast of the University of Minnesota. Reflection curves of "as received" solid fracture surfaces were measured and are quite similar to each other. One segment from the Holbrook meteorite was sputtered by hydrogen and reflection curves again measured after total bombardment times of 33 minutes, $5\frac{1}{2}$ hours, and 55 hours corresponding to approximately 10^3 years, 10^4 years, and 10^5 years of solar-wind action, respectively. The reflection curves of the original surfaces are shown in Figure 3. The various reflection curves for the bombarded Holbrook segment are shown in Figure 4. Figure 5 is a composite photograph illustrating the darkening by hydrogen bombardment. The original surface was composed of crystallites, some similar to quartz, with some darker inclusions and small reddish-brown areas. Under bombardment, the reddish-brown areas of the original surface become dark gray, very similar in appearance to the surface of some metal oxides (such as iron oxide) after bombardment. This demonstrates again the reduction in color by bombardment. After 55 hours of bombardment the surface has a normal albedo of 0.09 and appears glazed. Elsässer[13] has estimated the albedo of interplanetary dust particles to be ~ 0.01. Our results with a large stony fragment indicate a much higher albedo.
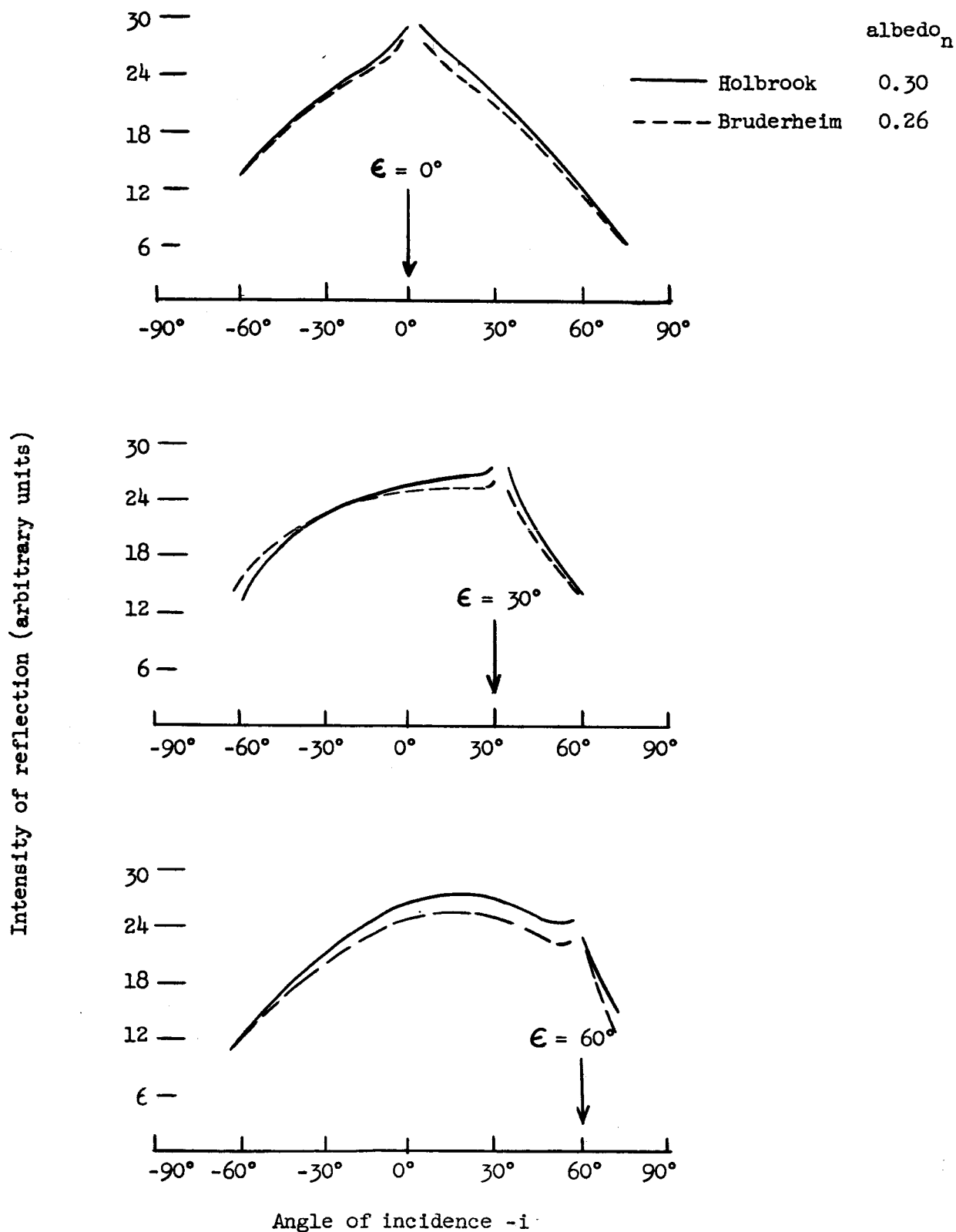
Figure 3 Reflection curves for original fracture surfaces of the Holbrook and Bruderheim meteorites.
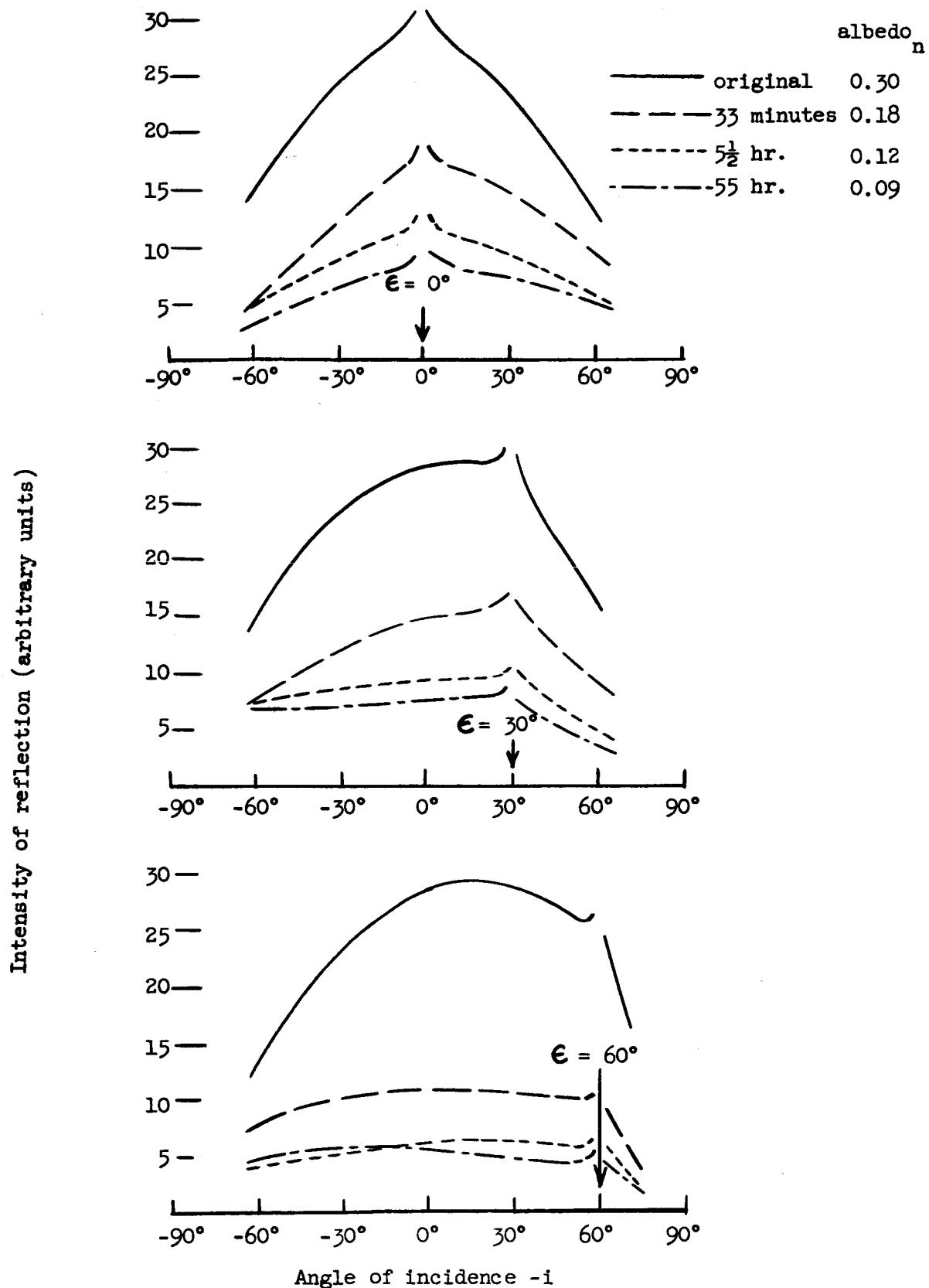
Figure 4   Reflection curves for the Holbrook meteorite after various durations of hydrogen bombardment.
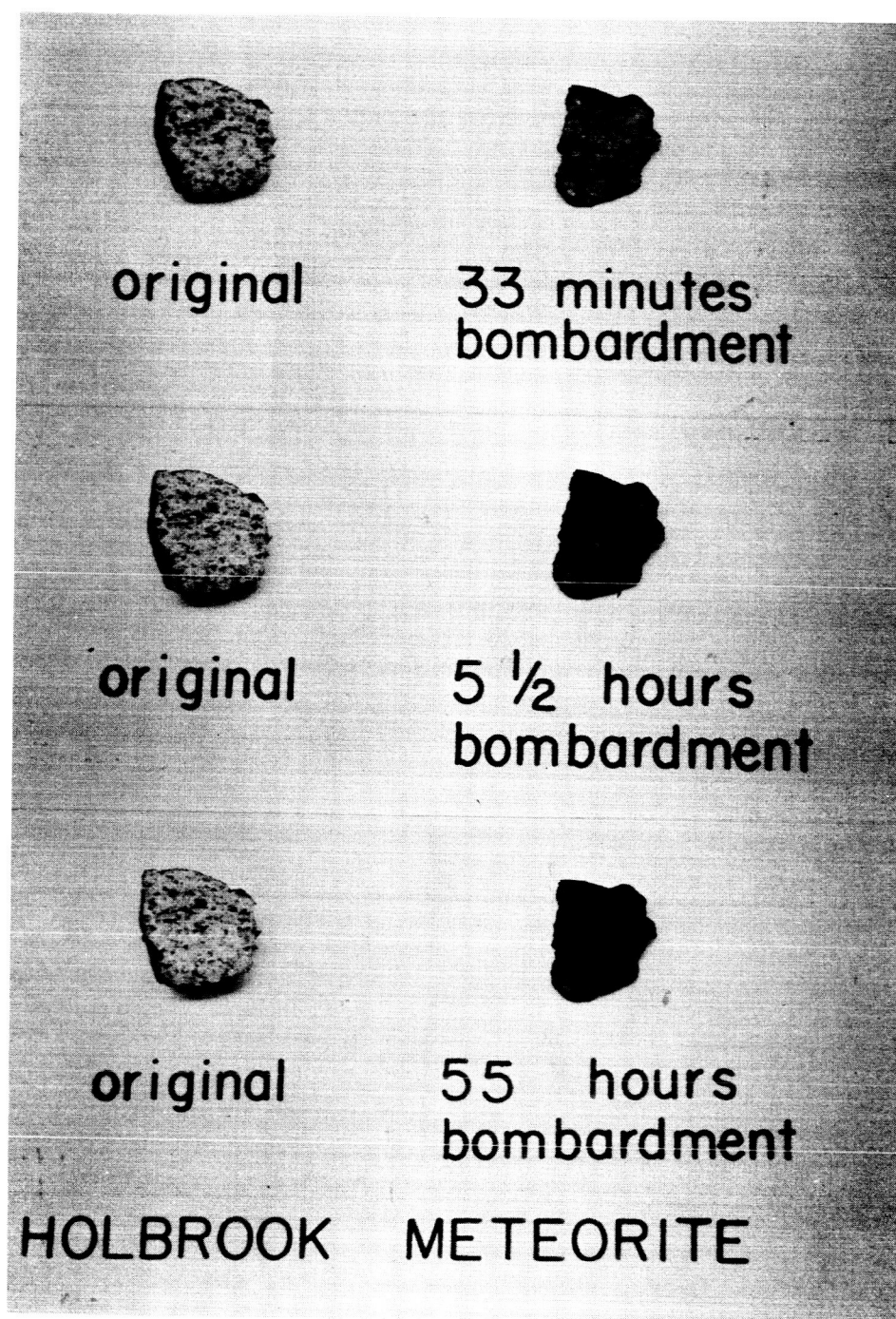
Figure 5 Darkening of fracture surface of Holbrook
meteorite by hydrogen-ion bombardment.

VI. REFLECTION CURVES AND NORMAL ALBEDOS OF BOMBARDED MATERIALS

Reflection curves and normal albedos of most of the materials we have studied under this contract are included here for reference in Figure 6-16. Some of these curves have appeared in previous reports in a somewhat different form.

Darkening and increase in backscatter are evident in almost every instance but the reduction in albedo and in specular-type reflection to that indicated for the lunar surface takes place only in powdered basalt, Fe_2O_3 powder, and Cu_2O powder. We have tried relatively few minerals and most likely many others would have reflection characteristics after bombardment as similar to those of the lunar surface as does basalt. Measurements of polarization characteristics are planned for the future in the hope that they will help to further specify the nature of the lunar surface.
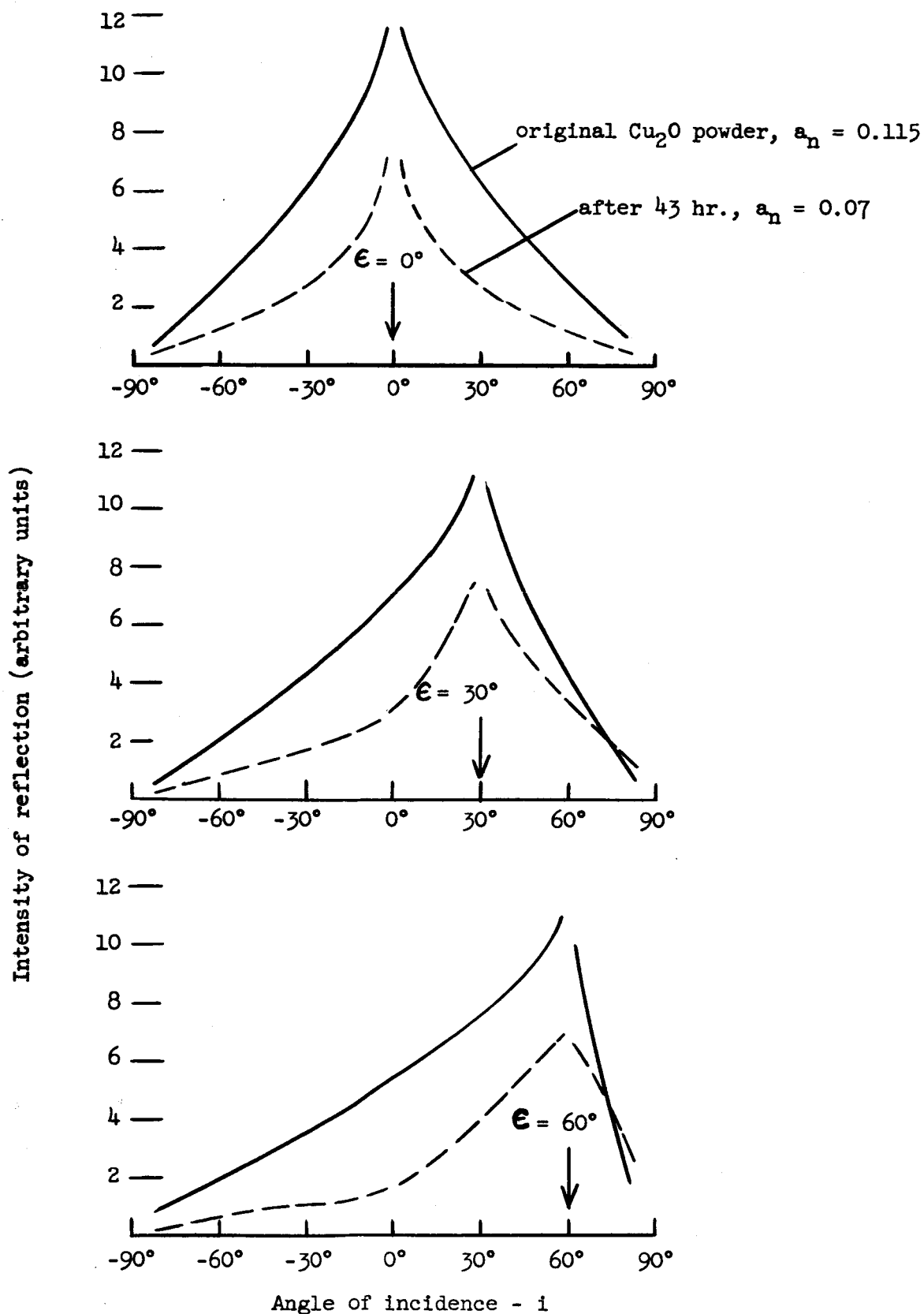
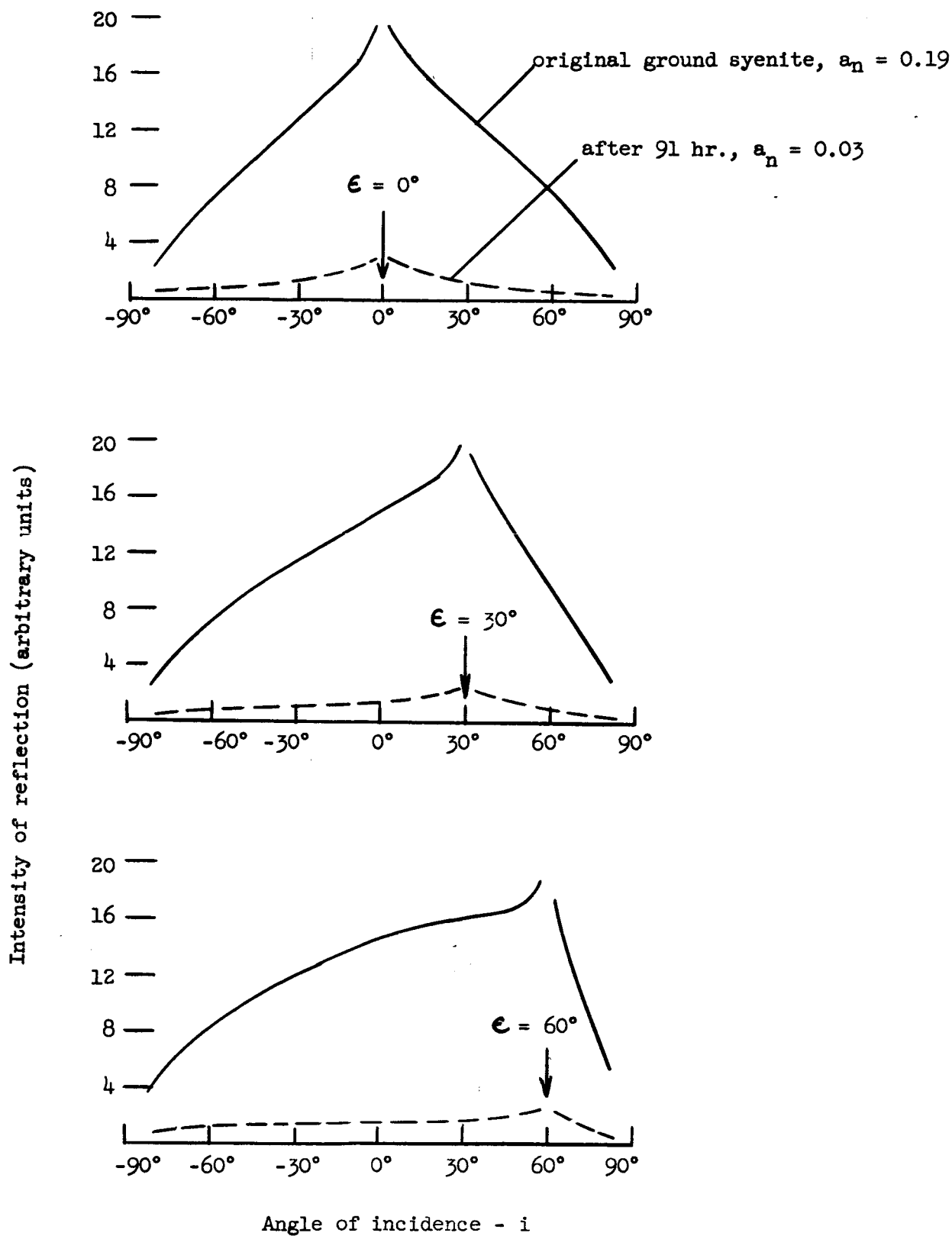Figure 6   Reflection curves in visible light for Cu_2O powder before and after 43 hr. hydrogen-ion bombardment.
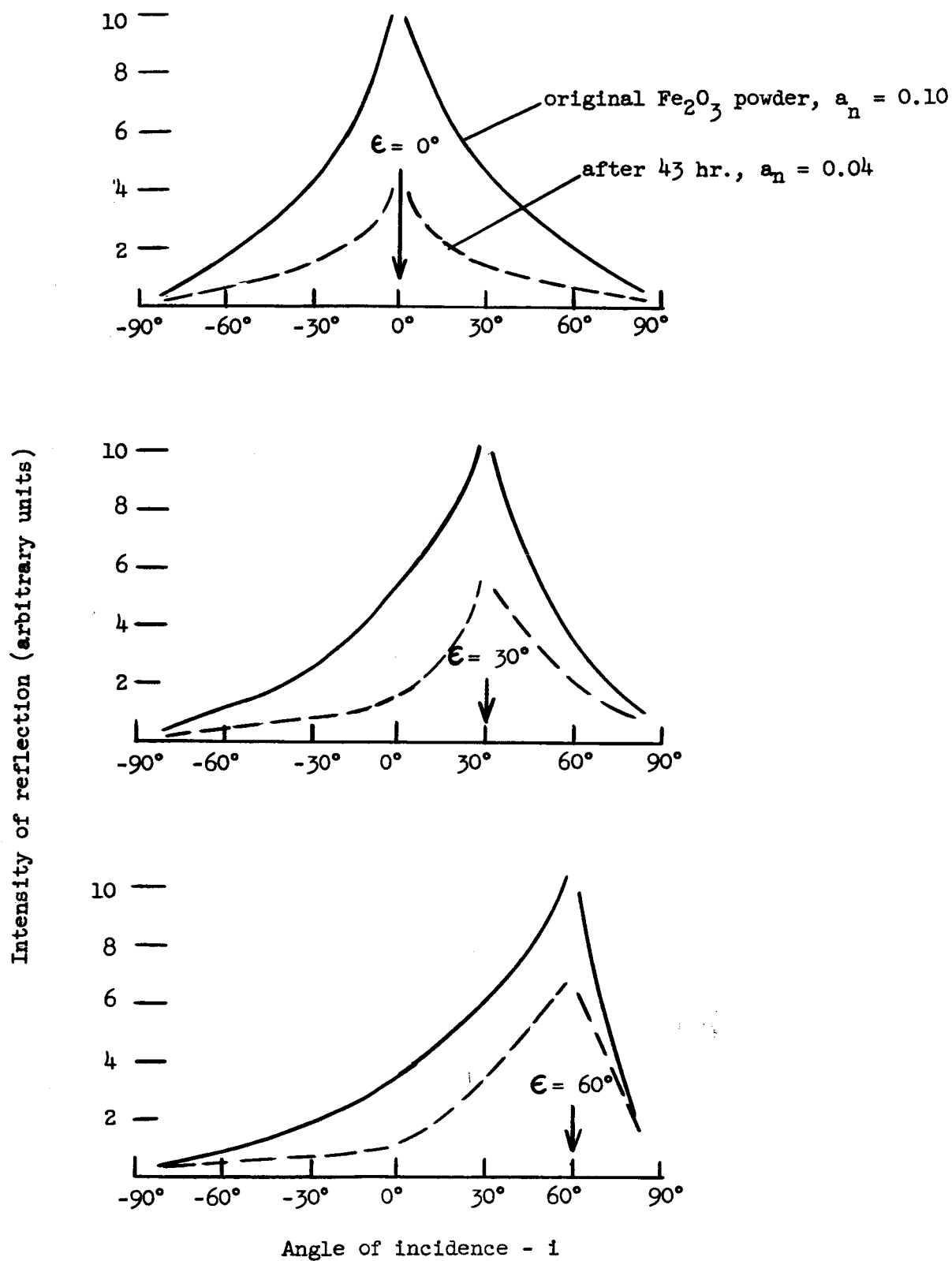
Figure 7   Reflection curves in visible light for Fe_2O_3 powder
before and after 43 hr. hydrogen-ion bombardment.
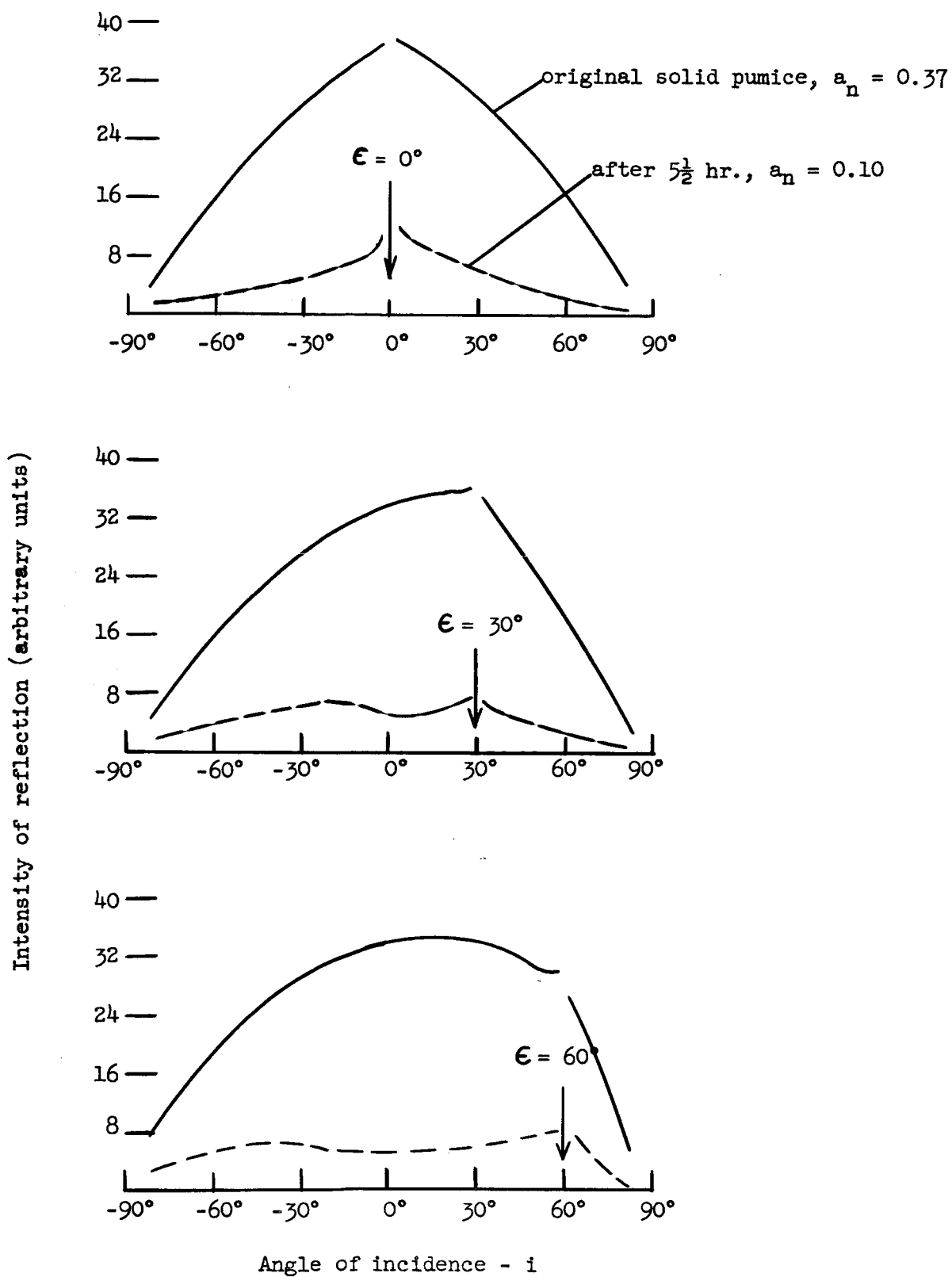
Figure 8   Reflection curves in visible light for solid pumice
before and after $5\frac{1}{2}$ hr. hydrogen-ion bombardment.
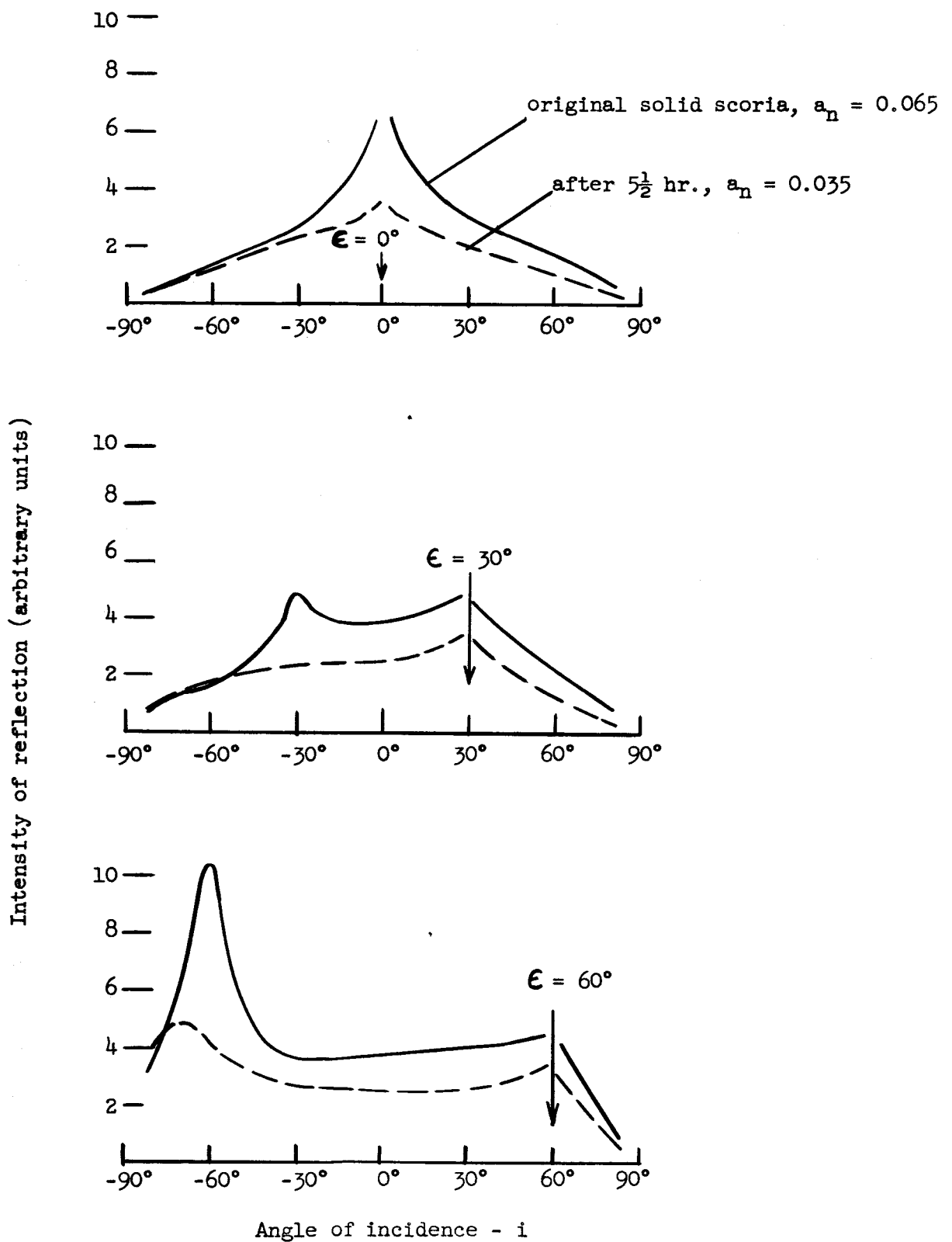
Figure 9 Reflection curves in visible light for solid scoria
before and after $5\frac{1}{2}$ hr. hydrogen-ion bombardment.
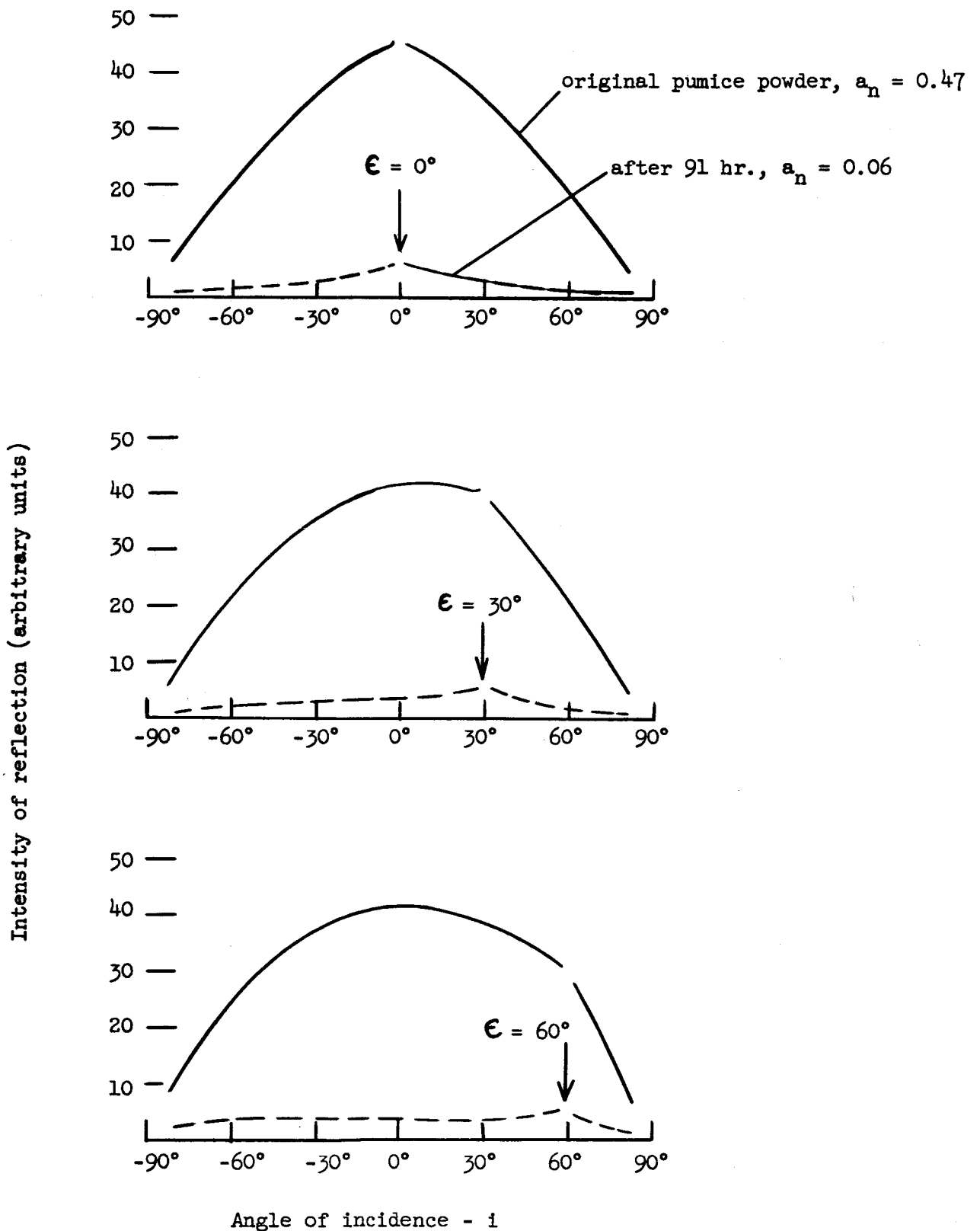
Figure 10   Reflection curves in visible light for pumice powder
before and after 91 hr. hydrogen-ion bombardment.
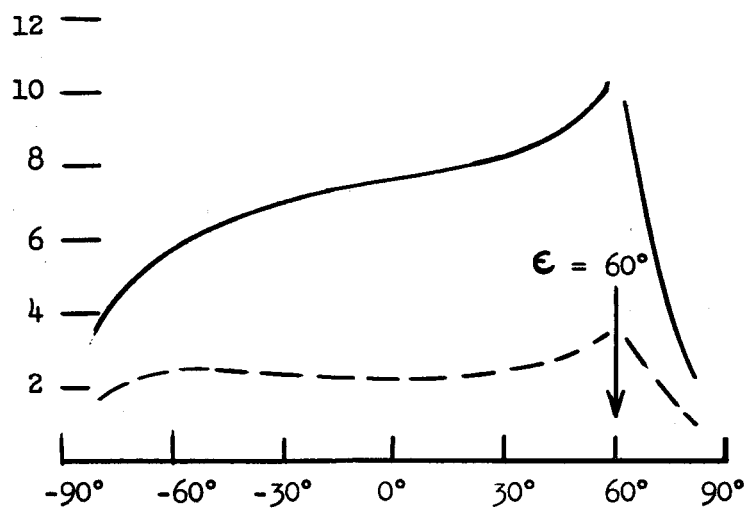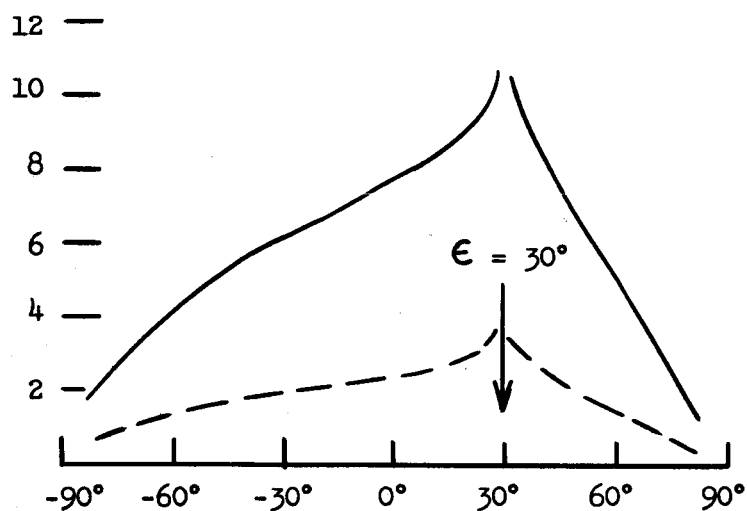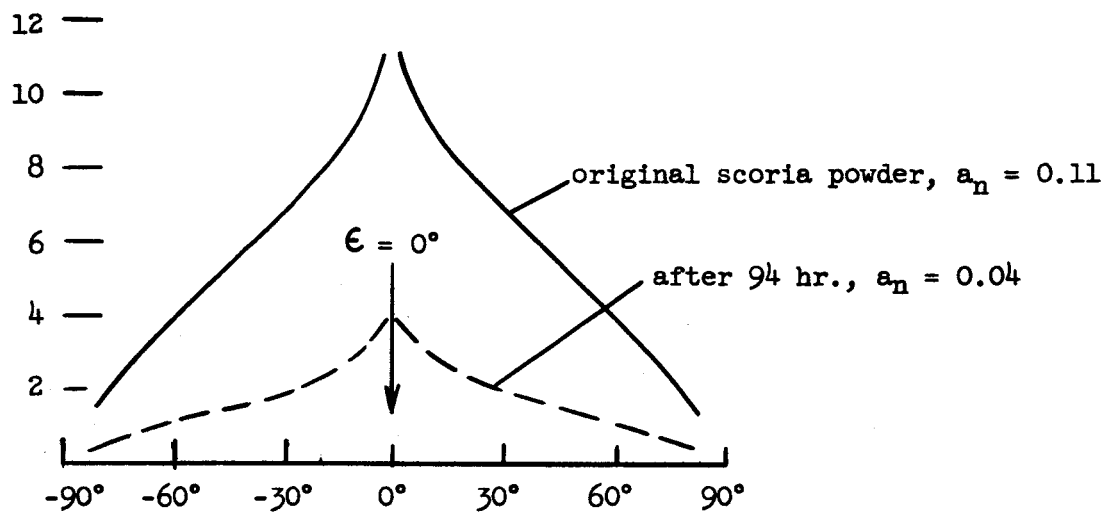
Figure 11   Reflection curves in visible light for scoria powder
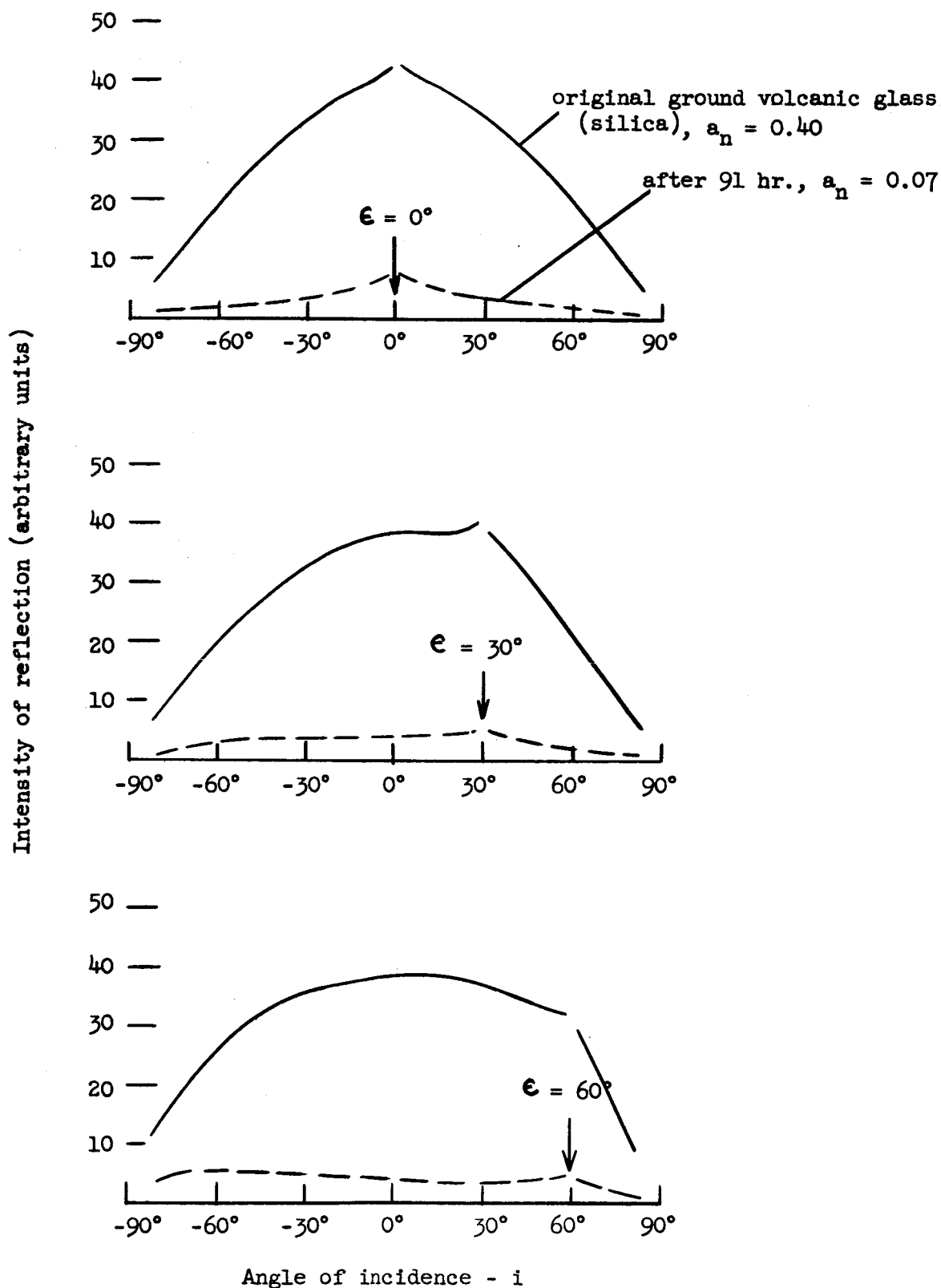before and after 94 hr. hydrogen-ion bombardment.
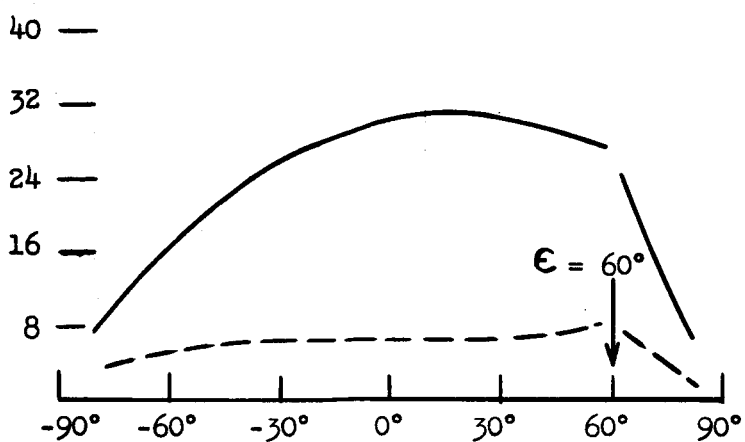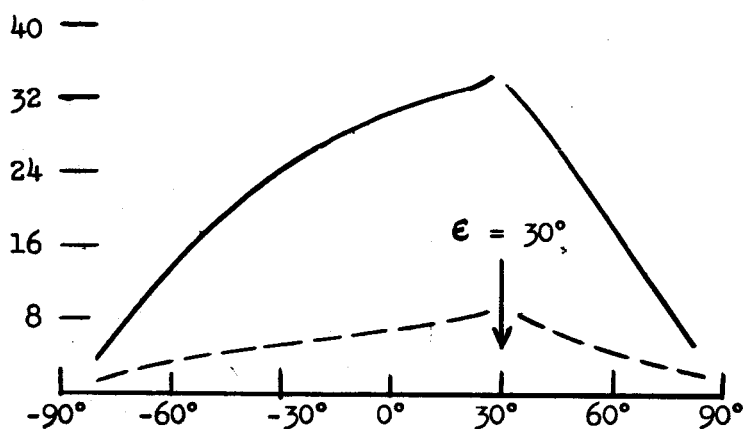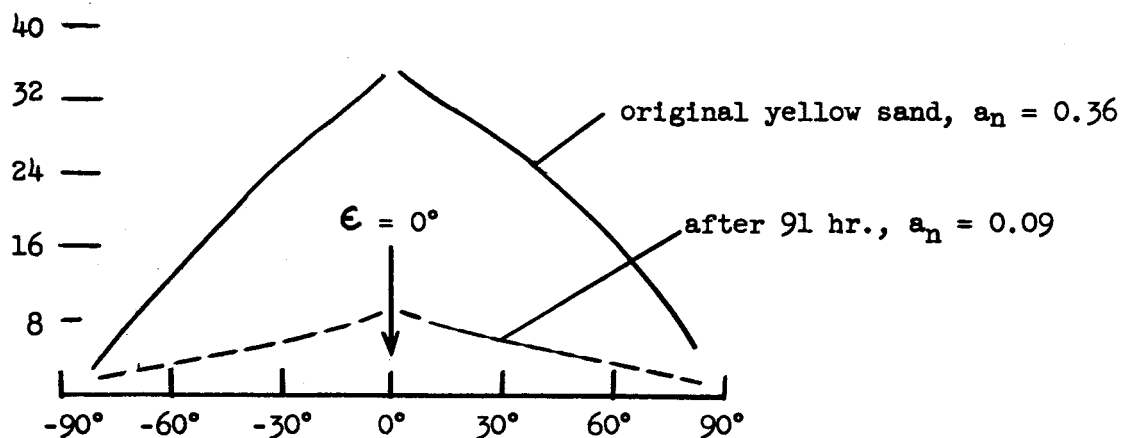
Figure 12 Reflection curves in visible light for yellow sand
before and after 91 hr. hydrogen-ion bombardment.

Figure 13   Reflection curves in visible light for ground syenite
before and after 91 hr. hydrogen-ion bombardment.

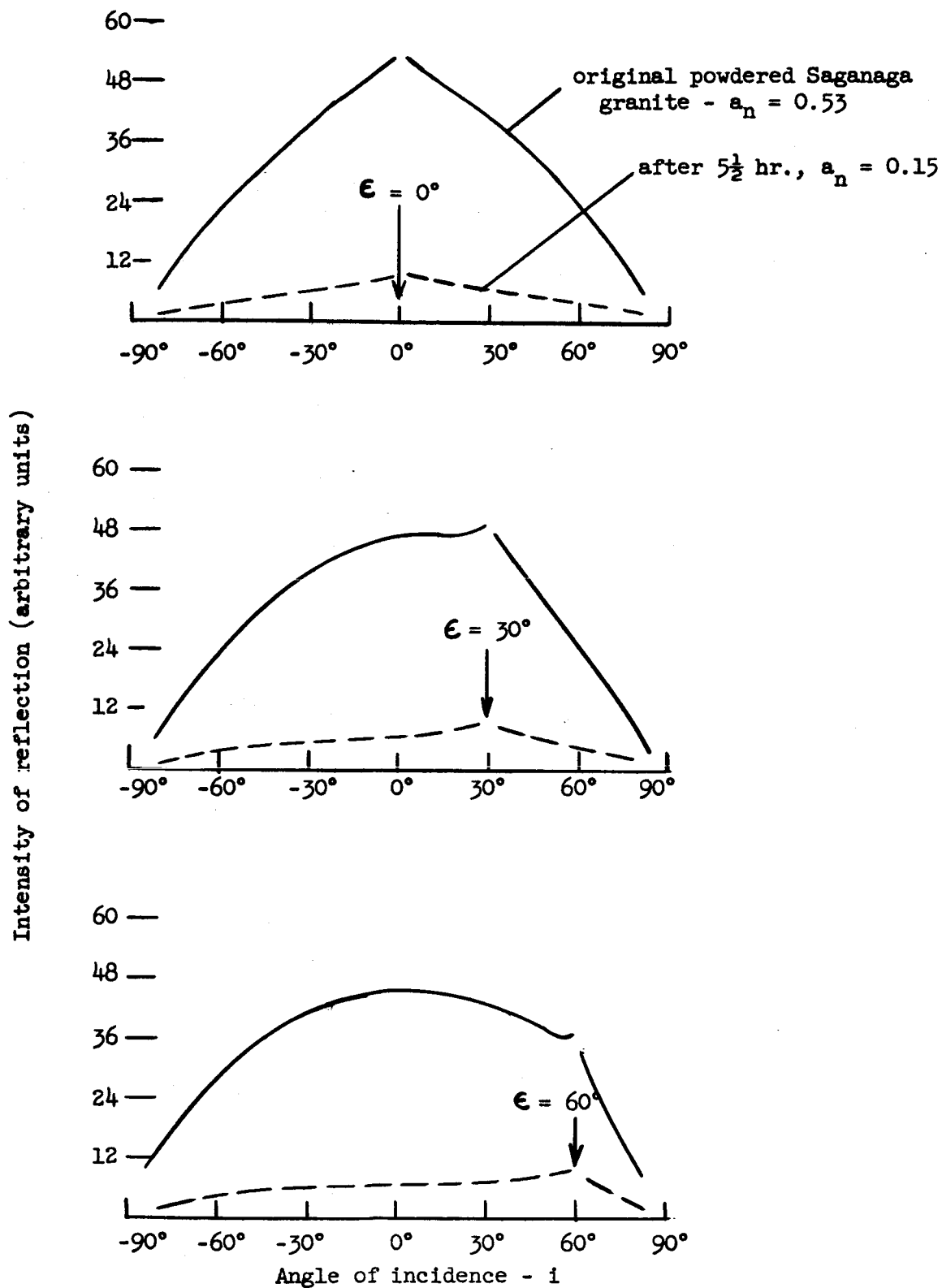Figure 14 Reflection curves in visible light for ground volcanic
glass (silica) before and after 91 hr. hydrogen-ion
bombardment.

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Figure 15 Reflection curves in visible light for powdered Saganaga
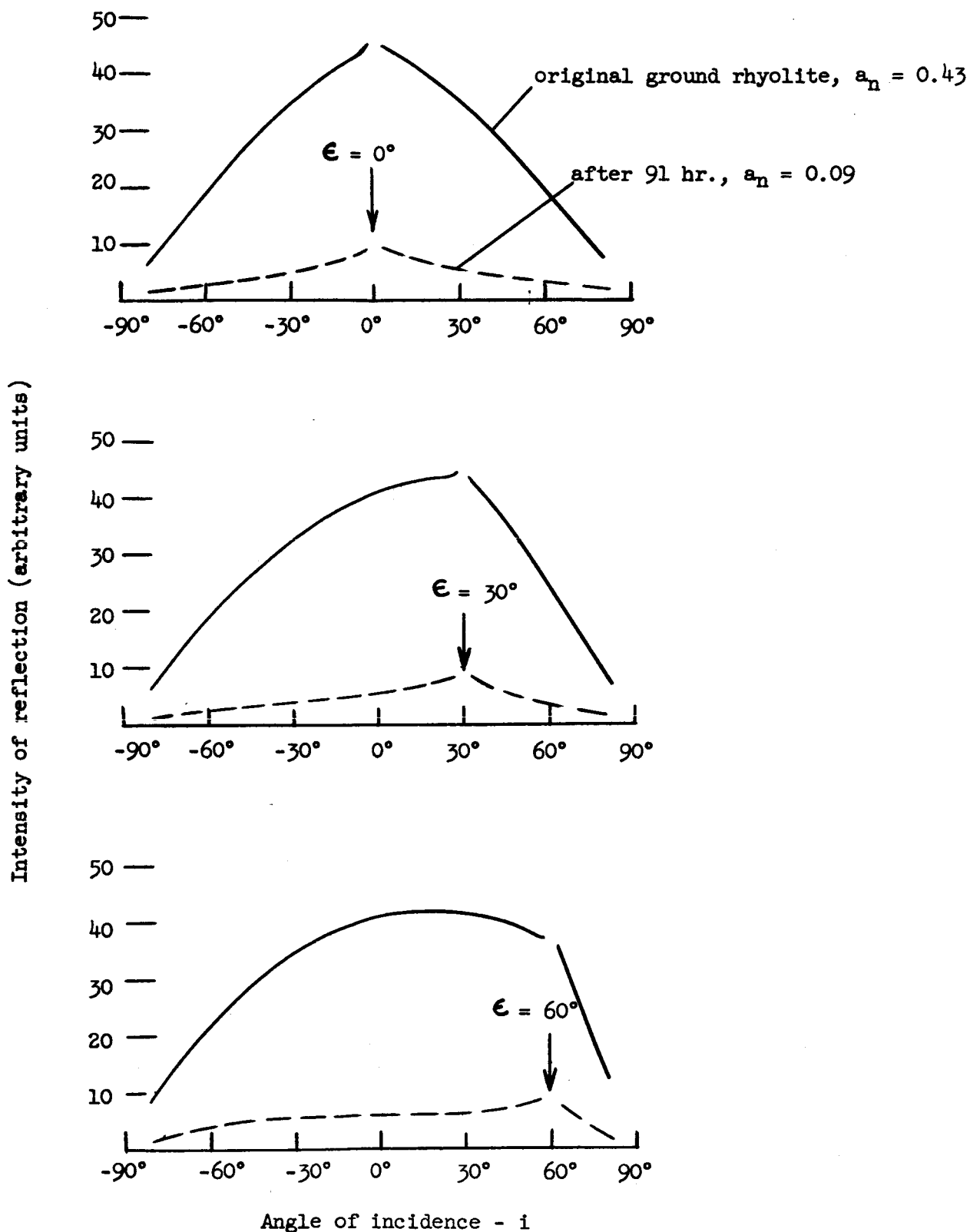granite before and after $5\frac{1}{2}$ hr. hydrogen-ion bombardment.

Figure 16   Reflection curves in visible light for ground rhyolite
before and after 91 hr. hydrogen-ion bombardment.

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APPENDIX A

Contribution to San Francisco Thermal
Radiation Symposium

SOLAR-WIND BOMBARDMENT OF A SURFACE IN SPACE

A

SOLAR-WIND BOMBARDMENT OF A SURFACE IN SPACE*

by
G. K. Wehner
Applied Science Division, Litton Systems, Inc.
Minneapolis, Minnesota

SUMMARY

The solar wind is described and its effects on surfaces are reviewed. Experimental results are given for materials subjected to simulated solar-wind bombardment. Among the effects discussed are sputtering-type erosion, chemical reaction with paint vehicles and reduction of oxide pigments, and production of lunar-surface optical characteristics in a basalt powder.

The surface of any body in space is under bombardment by high- and low-energy elementary particles. The question discussed here concerns the effects that occur on a surface under bombardment by the solar wind, that is, by low-energy protons and α-particles. From astrophysical observations and measurements with Explorer X, Lunik II, and Mariner II, data on flux density, composition, and energies of the particles in the solar wind are now fairly well established. Under a quiet Sun, the data indicate a flux of 2×10^8 protons/cm^2-sec with an average velocity of 600 km/sec at Earth orbit distance from the Sun. The protons are accompanied by 15 percent as many α-particles with the same velocities. Under solar-storm conditions, the flux and the particle velocities increase to much higher values. Under normal conditions, the bombarding energies are up to 1.85 keV for protons and 7.4 keV for α-particles; under solar-storm conditions, the energies are about 5 keV for protons and 20 keV for α-particles.

One can simulate these solar-wind bombardment conditions in the laboratory and, with much higher flux densities for short bombardment times, obtain measurable sputtering effects and surface damage. With the goal of studying possible modifications of the lunar surface, measurements were performed with mass separated H^+, H_2^+, and H_3^+ beams (ref. 1) and in low-pressure, hydrogen plasmas. One has to distinguish between purely physical effects, such as crystal damage, or sputtering, and superimposed chemical reactions between hydrogen and compounds such as oxides. Figure 1, for instance, shows the sputtering yields for protons on copper, in the energy range from 1 to 5 keV. The yields have a rather broad maximum in the range of solar-wind bombardment energies. The sputtering rates are rather small and amount to only about 1 Å/year for copper and 0.5 Å/year for iron. For many oxides the rates are roughly in the same range as that for iron. Thus, the Moon should have lost a layer 17 cm thick in 4.5×10^9 years, or a 1-cm-thick copper plate would be sputtered away in approximately 10^8 years. Physical sputtering will, therefore, hardly present any erosion problems in space missions. These results have been reported in detail in a recent paper (ref. 2).

More interesting effects arise from the cementing together of powder particles by sputtered atoms, from chemical reactions, or from the bombardment-induced breakup of molecules. Experiments with metal targets and metal-, oxide-, and rock-powder samples
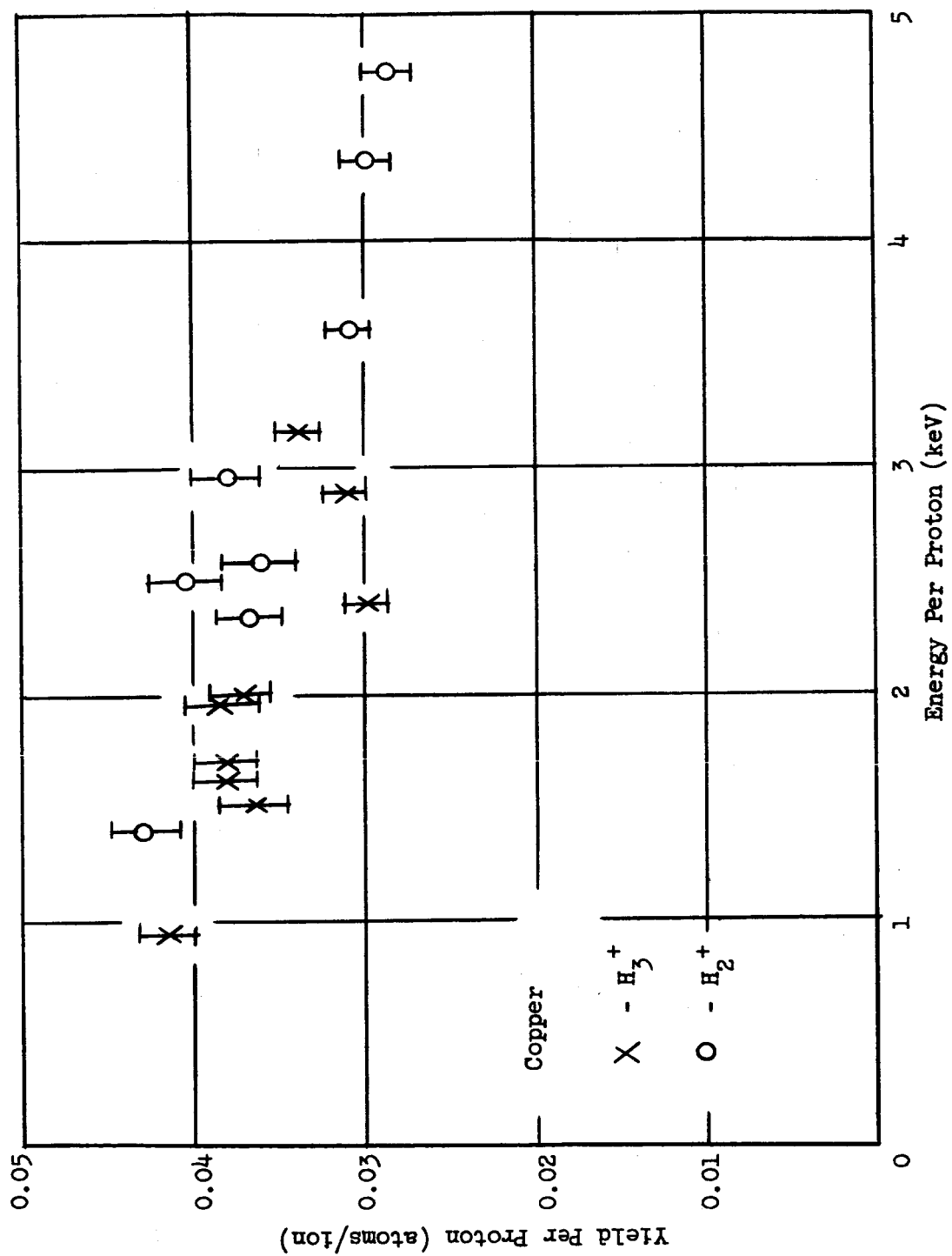
Figure 1 Sputtering yields of copper under proton bombardment
(from ref. 1)

demonstrate the leveling and smoothing of macroscopic surface features, the etching of polished surfaces (because differently oriented grains have different sputtering rates), and the cementing together of loose particles into a porous, brittle, fibrous crust. We have observed that many compounds, such as white oxides, darken under the bombardment because oxygen is more likely to escape in the breakup process resulting in a metal enrichment at the surface. Under noble-gas ion bombardment, black CuO is first converted into red Cu_2O and finally becomes covered with a very porous Cu layer. Under hydrogen ion bombardment we observed an immediate conversion to metallic copper. X-ray diffraction analysis shows that the red Fe_2O_3 changes into Fe_3O_4, FeO, and Fe under ion bombardment. Very pronounced chemical effects were observed in the case of tin bombarded by hydrogen ions. Here, the hydrogen combines with the tin and forms the volatile SnH_4, which results in much higher apparent sputtering rates. The controlled ion bombardment of insulator surfaces in a plasma was made possible with a recently developed technique in which a high-frequency voltage provides the necessary neutralization of surface charges at the target (ref. 3). Many of these experimental results are given in a paper on the modification of the lunar surface by solar-wind bombardment (ref. 4). One interesting result concerns the back reflection properties of surfaces bombarded by the solar wind. This is shown in figure 2, which shows our measurements of the visible light reflected in a
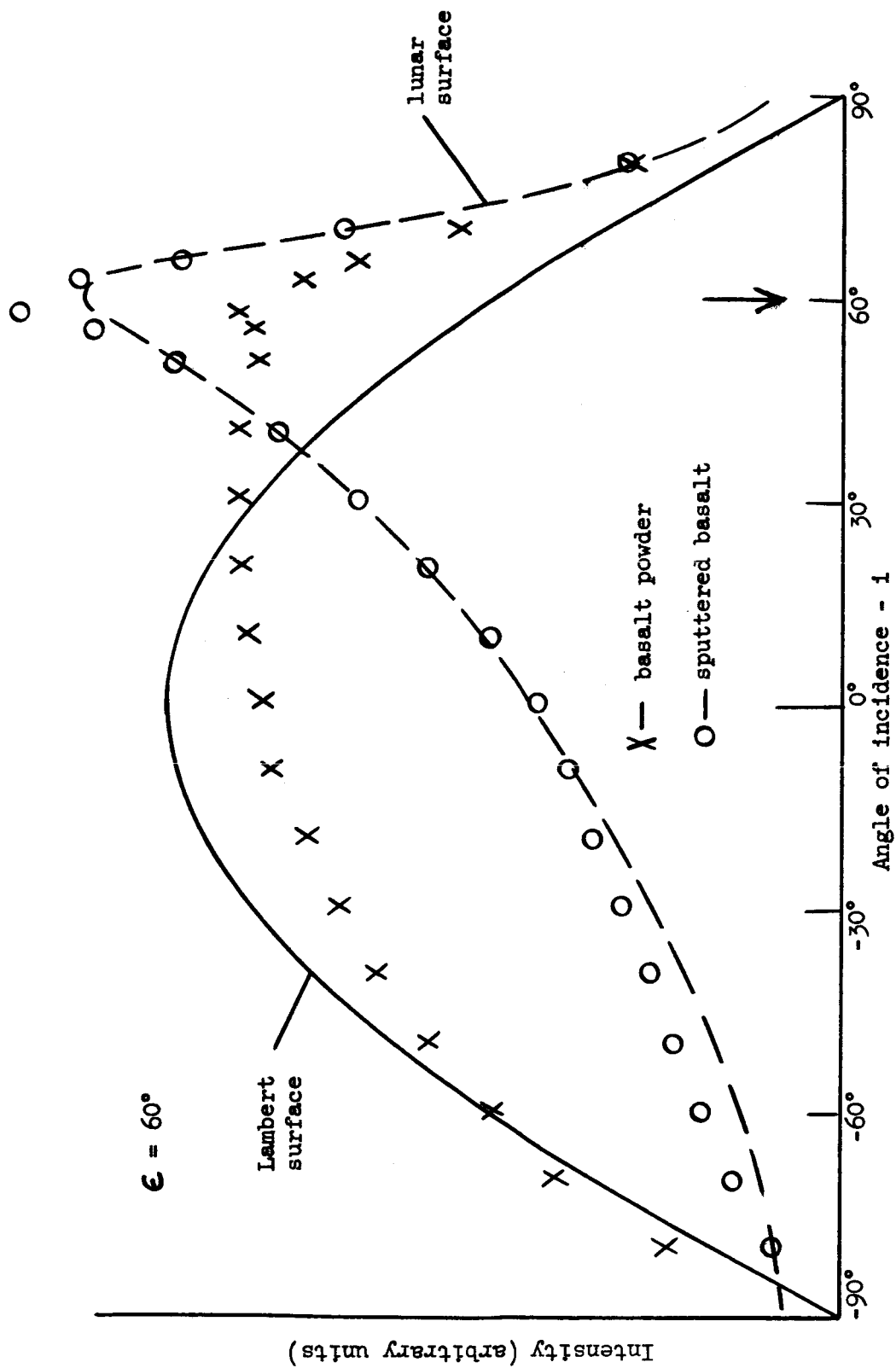
Figure 2 Angular light reflection properties of basalt powder before and after the equivalent of about 10^6 years of solar-wind bombardment.

direction 60° to the surface normal as a function of the angle of incidence of the incoming light. A basalt powder, with grain size 2 to 10 microns, provides a surface which resembles a Lambert surface. When this basalt powder is bombarded for the equivalent of 10^6 years of solar-wind bombardment, the surface is changed to a very open "fairy castle" structure (ref. 5) with radically different light reflection properties. With a fixed observation (or reflection) angle of 60°, a strong back-reflection peak appears at an incidence angle of 60°, very closely resembling the characteristic back-reflection peak in the corresponding curve for the lunar surface. Figure 3 shows how the surface of basalt powder darkens with bombardment time. The bombardment thus provides an explanation for the low albedo of the lunar surface.

The times involved here for obtaining visible effects are so long that we did not anticipate that spacecraft thermal-control paints would undergo measurable changes in only a few years. However, some exploratory work gave a rather surprising result. Paint samples (ZnO in methyl silicone binder) develop a visible brownish or tan color together with some glossiness at bombardment times equivalent to only five years of solar-wind bombardment. Figure 4 shows how the angular light reflection changes. Here, the observation direction was 30° to the surface normal. One notices the increased specularity of the reflection when the beam impinges at -30°. Measurements (with a Beckman DK2 with integrating sphere)

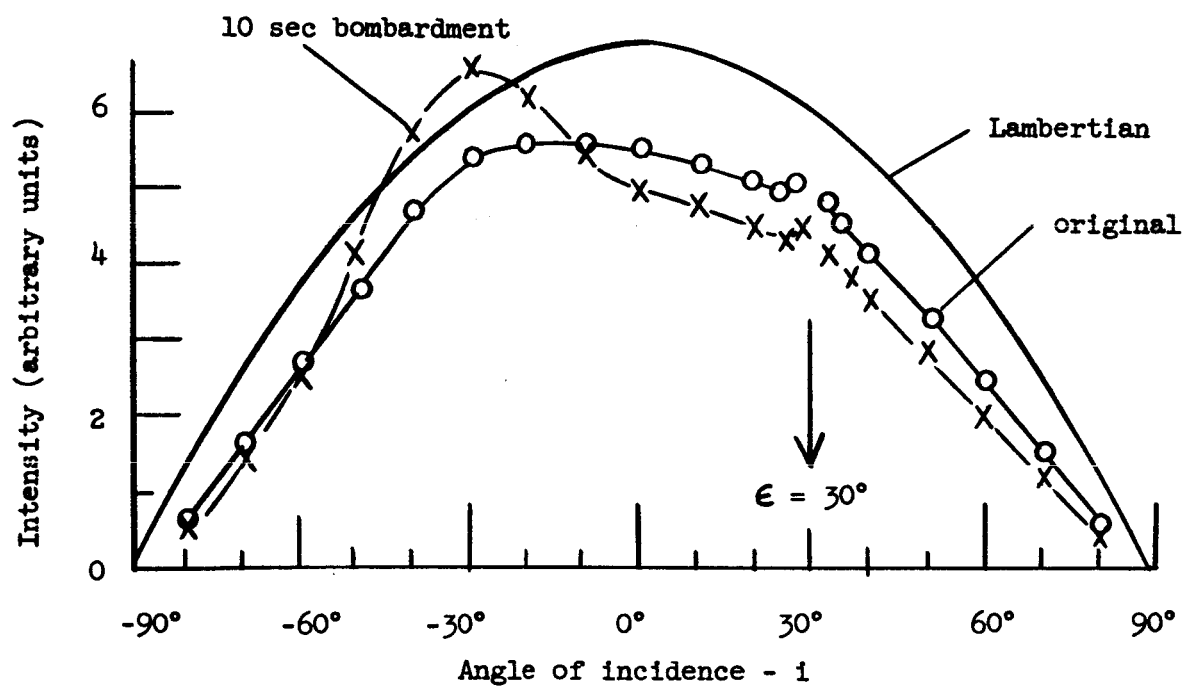Figure 3 Darkening of basalt powder under simulated solar-wind bombardment.

Figure 4 Angular light reflection of a spacecraft paint (ZnO in methyl silicone binder) before and after the equivalent of 5 years of solar-wind bombardment. Angle of observation (or reflection), 30°.

of absorptance in the visible part of the spectrum show a rather pronounced change, as shown in figure 5. The hydrogen plasmas used in these studies are strong ultraviolet radiation sources. The effects, however, are not caused by the ultraviolet radiation, as shown in an experiment in which part of the sample was covered with a thin quartz foil. The effects seem to be caused predominantly by chemical reactions of the protons with the binder. In the case of metal surfaces, we are in agreement with recent work by Anderson (ref. 6) who found very little change in thermal radiation properties after the equivalent of a few years of solar-wind bombardment. In the case of more complex materials, such as spacecraft thermal-control coating, more serious research effort is warranted. We cannot exclude the possibility that serious problems will arise in violent solar storms, in missions closer to the Sun, in missions of long duration, and in ion-engine environments.
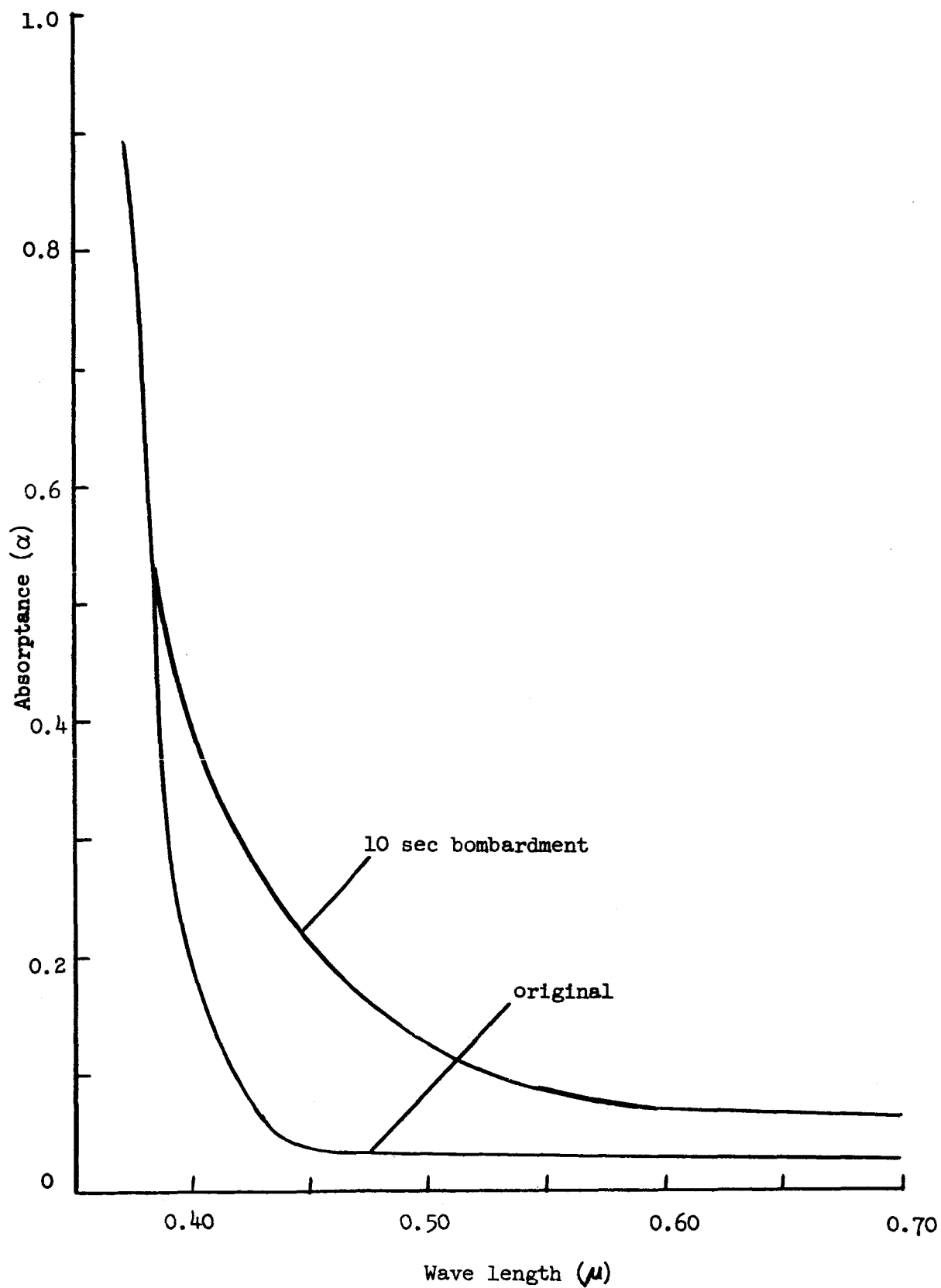
Figure 5 Spectral absorptance of a white paint (ZnO in methyl silicone binder) before and after simulated solar-wind bombardment.

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